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ORIGINAL ARTICLE

Load-bearing capacity of artificially aged zirconia fixed dental prostheses with heterogeneous abutment supports

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Abstract Aim of this in vitro study was to investigate the effect of artificial ageing and differential abutment support on the load-bearing capacity of zirconia posterior four-unit fixed dental prostheses (FDPs). Thirty-six FDPs were fabricated using CAD/CAM technology and divided into three groups. Specimens in the first group were cemented onto tooth analogues with simulated periodontal resilience, in the second group onto a dental implant and a tooth analogue, but in the third group only onto implants. Half of the samples in each group underwent artificial ageing. Afterwards, all FDPs were loaded until bulk fracture in a universal testing machine. Load-displacement curves and forces at fracture were recorded and results were statistically analysed using ANOVA. Load-bearing capacities within the different test groups averaged as follows (control/artificially aged): tooth–tooth supported (2,009/1,751 N), tooth–implant supported (2,144/1,935 N) and implant–implant supported (2,689/2,484 N). Artificial ageing as well as differential abutment support did have a significant influence on the fracture strength of the zirconia FDPs. Implant-retained prostheses demonstrated the highest load-bearing capacity, while resilient support was demonstrated to be unfavourable. According to these in vitro results, zirconia four-unit prostheses may be promising for application in posterior areas with all three support scenarios (implant-assisted, tooth-retained, or implant–tooth-interconnected prostheses). However, the restorations' mechanical strength may expected to be significantly influenced in situ by ageing of the material on the long term.

Keywords Zirconia FDPs · Artificial ageing · Load-bearing capacity · Implant-supported prosthesis · Implant–tooth-interconnected restorations

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Introduction

In recent years, zirconia restorations have become increasingly important in prosthodontics. The special mechanical characteristics of zirconia have led to its wide application, even on long-spanned fixed dental prostheses (FDPs). Due to a special reinforcement process—transformation from the tetragonal to the monoclinic phase at a crack tip [1]—zirconia shows the greatest flexural strength and fracture toughness ever reported for a dental ceramic material [2].

Although the transformation reinforcement appears to be favourable with respect to bearing high loads, this process also has negative long-term effects. Water and relatively low temperatures may also initiate a slow transition of the tetragonal to the monoclinic phase, a phenomenon called low-temperature degradation (LTD) [3]. This degradation is accompanied by an increase in the monoclinic phase content, and may greatly reduce strength and toughness [4–6], thus reducing the lifetime of the restoration. Failures of zirconia prostheses due to ageing have called into doubt the application of this material in other fields of clinical medicine, e.g., orthopaedics [7].

It is obvious that material fatigue may influence the characteristics of all-ceramic restorations. For an all-ceramic restoration to be viable, its load-bearing capacity should exceed natural maximal bite forces over protracted periods. Published data on the effect of ageing on the fracture strength of zirconia are inconsistent. Some studies report that there is no statistically significant influence of artificial ageing on the load-bearing capacity of zirconia restorations [8–10], while other investigators did detect a significant impact [11–13]. Since there is evidence of such detrimental influence, simulation of ageing is essential when load-bearing capacity of all-ceramic prostheses is investigated, if clinical conditions are to be faithfully represented.

As mentioned above, zirconia can be employed for various standard dental treatments, i.e., fixed dental prostheses supported by natural teeth. Nonetheless, in innovative treatment methods, not only natural teeth but also dental implants or even a combination of implants with natural teeth can be used to support different kinds of prostheses. For example, if the remaining teeth are few or unfavourably distributed in the jaw, if there is bone inadequacy or potential danger of damaging adjacent innervating tissues, the only adequate treatment may be implant-assisted prostheses or restorations in which the implants are splinted with natural teeth. However, there is not yet any evidence whether new ceramic materials such as zirconia can be used in these fields of prosthodontics. Since all-ceramics are vulnerable to tensile stresses, and resilient support increases maximum tensile stresses [14], the mobility mismatch of the differential abutments may be a further factor affecting the load-bearing capacity of zirconia FDPs. Hence, implant-retained or mixed restorations in combination with zirconia have to be further investigated in order to evaluate the potential applications of this material.

The aim of this in vitro study was to evaluate the influence of artificial ageing on the load-bearing capacity of four-unit zirconia FDPs. Three different support scenarios (restorations supported by model teeth with simulated periodontal resilience, implant-assisted prostheses and implant-to-tooth-interconnected FDPs) were chosen to model modern applications of zirconia. The hypotheses to be investigated were: (a) that thermomechanical cycling has a significant impact on the load-bearing capacity of all types of FDPs, and (b) that the type of abutment support significantly influences the forces at fracture.

Materials and methods

Manufacture of master models

Two frasaco typodont model teeth (upper first premolar and upper second molar) were prepared with a chamfer finishing line. Individual impressions of the whole prepared teeth (crown and root) were taken. The produced moulds were then casted with polyurethane resin (PUR; Alpha-Die-Top; Schütz Dental, Rosbach, Germany), so that PUR teeth analogues were manufactured. The roots of the tooth analogues were covered with a layer of elastic latex material (Erkoskin; Erkodent, Pfalzgrafenweiler, Germany), in order to simulate natural periodontal resilience. Afterwards, model teeth or implants (Straumann BoneLevel 4.1 mm RC, SLActive 10 mm; Straumann Institute AG, Basel, Switzerland) were embedded in a polyurethane block (PUR) to mimic clinical conditions for a four-unit FDP as follows: premolar and molar model teeth, a premolar model tooth and an implant in the molar region, and implants in both the premolar and molar regions. Cementable titanium abutments (D 5 mm, GH 3 mm, AH 4 mm, RC; Straumann Institute AG, Basel, Switzerland) had been previously screwed into the implants with a system-specific ratchet and a torque of 25 Ncm. The distance between the apexes of the support structures (teeth or implants) in the PUR block was 23 mm, corresponding to the average clearance between a first premolar and a second molar. Thus, three master models were produced, corresponding to three different support scenarios.

Manufacture of the FDPs

The master models were optically scanned, in order to fabricate Y-TZP frameworks (zerion™; Straumann CAD/CAM GmbH, Freiburg, Germany), using a computer-aided design and computer-aided manufacturing (CAD/CAM) system (etkon™; Straumann CADCAM GmbH, Gräfelfing/Munich, Germany). From each master model, 12 frameworks were produced—a total of 36. Connector cross-sectional areas were 12.5, 15.6 and 11.6 mm^2 (from mesial to distal). The connector width and height differed by less than 0.2 mm between frameworks. All frameworks were veneered according to the manufacturer's instructions, with the recommended ceramic (Vita VM 9; Vita Zahnfabrik, Bad Säckingen, Germany) and using a slurry technique. The homogenous dimensioning of the veneering layer—with layer thickness between 0.5 and 1.2 mm (according to position)—was guaranteed by use of various silicone templates, which were prepared in advance with a wax-up.

The FDPs were then divided into three homogenous groups according to their retainers. In group I, restorations were supported by model teeth with simulated periodontal resilience, in the group II by the combination of a tooth analogue and an implant, and in group III by implants only (Fig. 1). The model teeth were fabricated through the same technique as for the master models, while implant abutments were also the same as used for the master models. Finally, the FDPs were cemented on the abutments with glass-ionomer cement (Ketac-Cem; 3M Espe, Seefeld, Germany) and embedded in a PUR base.

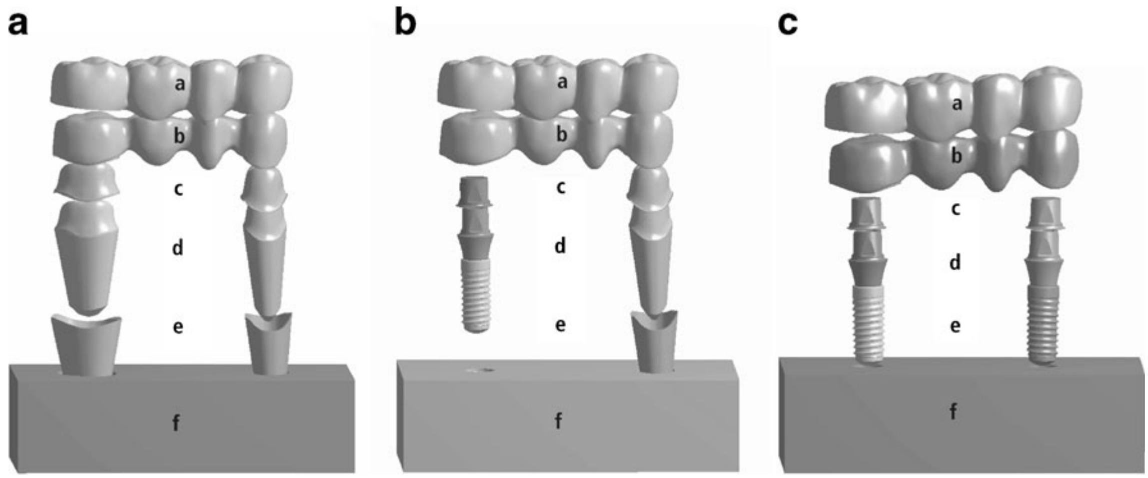

Fig. 1 Expanded views of tested FDPs with different support scenarios: **a** tooth-retained, **b** tooth-implant interconnected, **c** implant-retained. Identification of the different components: *a* veneer layer, *b* zirconia framework, *c* cement layer, *d* abutment structure, *e* rigid/resilient support structure, *f* model base

Artificial ageing

Half of the specimens in each group (n=6) underwent artificial ageing, which included storage in an aqueous environment as well as thermal and mechanical cycling. Thermocycling and mechanical loading both took place in an aqueous milieu (distilled water). At first, a total of 10,000 alternate thermal cycles were performed between 5 and 55°C, with a dwell time at each temperature of 30 s. Afterwards the samples were subjected to one million cycles of mechanical loading in a chewing simulator. In this procedure the load was applied according to a sinusoidal curve with a frequency of 2.5 Hz. Within 1 cycle the minimum load was 0 N and the maximum load was 100 N. The load was vertically transferred onto the centre of the middle pontic centre via a carbide tungsten ball (diameter 6 mm) on an interposed tin foil (thickness 0.2 mm). For the time periods that the specimens were not thermally or mechanically loaded they were stored in distilled water at a temperature of 36°C. Overall, the whole aqueous simulation lasted 200 days.

Determination of the load-bearing capacity

All specimens were finally subjected to a static load-to-fracture test in a universal testing machine (Type 20K; UTS Testsysteme, Ulm-Einsingen, Germany). The testing machine moved vertically at a crosshead speed of 1 mm min^{-1}. Similar to the cycling mechanical loading, the load was transferred onto the pontic centre via a tungsten carbide ball (diameter 6 mm) on an interposed tin foil (thickness 0.2 mm). A sudden decrease in force of more than 50 N was regarded as an indication of failure, and the maximum recorded force up to this point was defined as load-bearing capacity.

Fractographical analysis

After loading, the fracture behaviour of all specimens was primarily inspected by eye. Additionally, detailed analysis of fracture patterns and fracture surfaces was performed by light microscopy (M3Z, Wild, Heerbrugg, Switzerland) and for representative specimens by scanning electron microscopy (SEM, Leo 1455VP; Carl Zeiss, Jena, Germany).

Statistical analysis

Statistical evaluation of the results was performed using SPSS for Windows, version 17.0 (SPSS software, Munich, Germany). Normal distribution of data and homogeneity of variance were checked using the Kolmogorov–Smirnov and Levene tests, respectively. To determine whether retainer's mobility or artificial ageing had a statistically significant impact on the fracture strength, two-factorial analysis of variance (ANOVA) was performed. Additionally, individual variations between differently supported FDPs were checked by ANOVA with post-hoc Scheffé test. The level of significance was set at 0.05.

Results

All FDPs survived artificial ageing without any obvious defects, and terminal load-at-failure testing could be performed with all specimens. After the testing had been completed, total fractures running through both the core and the veneer were observed for all FDPs. The vast majority of the frameworks (30 out of 36) failed in the centre of the middle pontic—between the second premolar and the first molar (fracture specification 1—FS1). With the other six specimens the fractures ran from the margin of the first premolar abutment to the occlusal area of the second premolar (fracture specification 2—FS2). In the test group of tooth-retained FDPs, ten specimens failed according to FS1 (Fig. 2) and two specimens according to FS2. With the implant–tooth-interconnected prostheses, eight specimens failed according to FS1 and four specimens according to FS2 (Fig. 3). For the implant-assisted FDPs, only failures according to FS1 were observed (Fig. 4). Simultaneously to total bulk fracture, extensive delamination of the veneer layer was detected for several specimens, not depending on the kind of support scenario (Figs. 2, 3 and 4). However, during load application no chipping of the veneer ceramic occurred, only Hertzian cone cracks were visible at the loading site, in the contact area of the tungsten carbide ball (Fig. 5). Even if these cone cracks took place at the occlusal loading site, further SEM analysis revealed that with all tested FDPs the fracture origin was located in the zirconia framework close to the core/veneer interface at the gingival embrasure (Fig. 6).

The recorded forces at fracture for each group are given in Table 1. Statistical comparison of mean values of the aged and the non-aged specimens found a statistically significant influence of artificial ageing on the load-bearing capacity ($p=0.032$). Furthermore, ANOVA also revealed a statistically significant impact of abutment support on the fracture strength ($p<0.001$). Individual comparison of the implant-retained prostheses with the FDPs on tooth analogues with simulated periodontal resilience gave a statistical significant difference for both the aged ($p<0.001$) and the non-aged ($p=0.02$) groups. Additionally, the implant-assisted aged group showed a significantly superior load-bearing capacity when compared with the mixed group ($p=0.001$). On the other hand, there was no significant difference between the implant-supported and combined prostheses of the non-aged groups ($p=0.064$).

Discussion

In this study, the effect of artificial ageing on the load-bearing capacity of zirconia FDPs supported by different abutment types was investigated in vitro. With in vitro studies, it is of crucial importance to follow a test set-up which faithfully imitates clinical conditions. Therefore, all laboratory steps were carefully performed following an experimental protocol which had already been successfully applied in previous studies [11, 12, 15]. The manufacturer's instructions were strictly followed for all materials and procedures.

In addition, materials used in this experiment were carefully chosen. PUR was preferred for manufacturing tooth analogues, as well as for embedding the FDPs, since its modulus of elasticity is similar to that of dentin and bone [16]. The abutment material has already been proved to have a significant influence during loading tests [14, 17]. Materials of high rigidity, e.g., alloys, support the supraconstruction to a greater extent and may lead to false results. PURs properties more closely approach those of dentin and thus more realistic results are obtained. At the same time, the choice of PUR as embedding material faithfully represents the bone's behaviour under loading. Moreover, the resilience of natural teeth was imitated through a layer of elastic latex material. According to Rosentritt et al. [17] it is necessary to apply an artificial periodontium during ageing and fracture testing so that the function of the periodontal ligament can be simulated. Rigidly supported teeth may also cause misleading results for the load-bearing capacity of the frameworks.

For the veneering layer, laminated specimens were loaded till fracture in our study. Ceramic chipping has been reported as one of the major complications arising in all-ceramic restorations [18]. It has also been implied that the veneering layer may protect the zirconia framework from the disadvantageous effects of the aqueous milieu [12]. These considerations have led some investigators to load unveneered specimens [19]. On the other hand, the core–

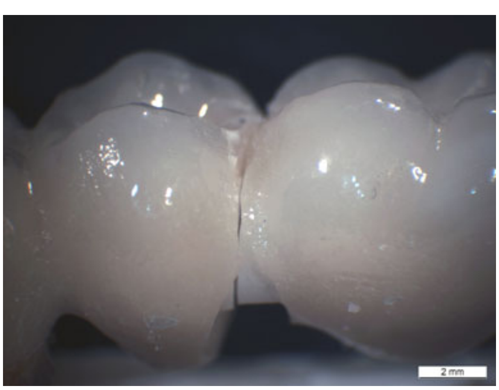

Fig. 2 Fractured sample of the tooth-supported group. Fracture specification 1

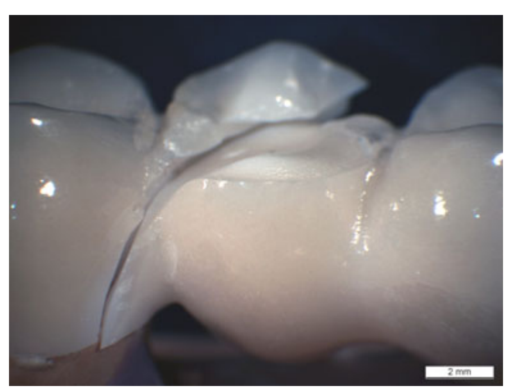

Fig. 3 Fractured sample of the tooth–implant-assisted group. Fracture specification 2

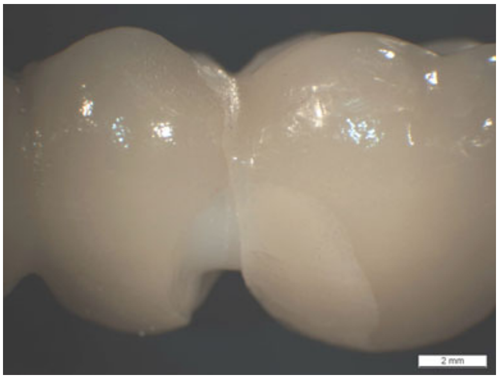

Fig. 4 Fractured sample of the implant-assisted group. Fracture specification 1

veneer interface has been reported to be the origin of catastrophic fractures of the core with all-ceramic FDPs [20]. Since the aim of the study was to evaluate the properties of the whole dental restoration, we opted to veneer all samples. Thus, clinical reality was more faithfully approximated and the tested specimens authentically represented dental prostheses.

The artificial ageing protocol was also carefully designed. According to Beuer et al. three parameters are necessary when simulating ageing in the dental environment [8]. Firstly, the aqueous milieu must resemble saliva in the oral cavity. Secondly, there must be thermal stressing corresponding to temperature alternations caused by hot and cold food as well as breathing. Finally, there must be mechanical cycling, representing natural loading while chewing, speaking and swallowing. In our experiment, specimens were stored for 200 days in distilled water at 36°C. Drummond reported that with zirconia the main decrease in strength occurs somewhere between 140 and 304 days of storage in an aqueous environment [21]. Thus, the bulk of the degradation is expected within the 200 days of water storage in our study. Moreover, Palmer et al. suggested a temperature range of 0 to 67°C for thermal stressing [22]. Thermal cycling between 5

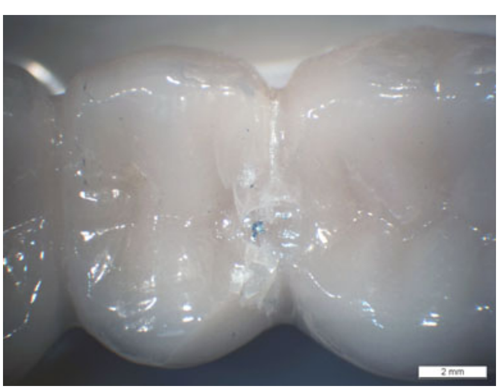

Fig. 5 Hertzian cone cracks at the loading point

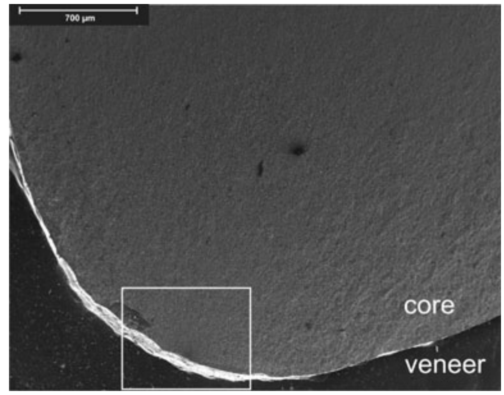

Fig. 6 Representative SEM image of the fracture surface of an FDP which failed in the middle pontic area. The fracture origin is located at the gingival embrasure of the pontic within the zirconia core (indicated by a *white box*)

and 55°C lies near the limits of this range and has already been performed by several other investigators [8, 12, 23, 24]. In addition, according to Gale et al., 10,000 thermal cycles corresponds to approximately 1 year of function [25]. As far as the mechanical cycling is concerned, it has been estimated that 800,000 contacts per year occur while a prosthesis is in service [17]. This means that the 1,000,000 cycles performed in this experiment simulated approximately 15 months of function. Finally, chewing forces have been reported to range between 20 and 120 N [26]. The 100-N force applied in our experiment lies well in the upper limit of these margins. Thus, the loads applied during mechanical cycling correspond to high levels of physiological chewing forces, and this can improve the estimation of the restoration's performance under more severe conditions.

In the present study, with both the artificial ageing procedure and the final fracture tests FDPs were occlusally loaded on the centre of the middle connector. The contact situation is of crucial importance when evaluating the load-bearing capacity of dental prostheses. Dittmer et al. tested different occlusion scenarios and reported that under the loading of four-unit zirconia FDPs, highest tensile stresses occur at the basal side of the middle connector [27, 28]. Furthermore, they found that homogeneous distribution of occlusal contacts may be favourable regarding the reduction of detrimental tensile stresses. In our study, occlusal forces were concentrated to only one point; this configuration was chosen in order to simulate the worst case scenario concerning the occlusal incidents occurring on all-ceramic prostheses. Moreover, a larger number of loading points (i.e., in the region of the cusps) was not intended to avoid chipping of the veneer ceramic. Indeed chipping is one of the major reasons for the clinical failure of zirconia restorations [29]; however, this survey was focused on the load-bearing capacity of the entire restorations (including bulk fracture of the zirconia core) and not on the failure of the veneer ceramic. Nevertheless, prior to

Table 1 Load-bearing capacity (newton) of differently supported and aged fixed dental prostheses

	Control specimens				Artificially aged specimens			
	MV	SD	Min	Max	MV	SD	Min	Max
Tooth–tooth (I)	2,009.4 b	174.1	1,779.2	2,246.8	1,751.1 b	270.5	1,389.6	2,091.0
Tooth–implant (II)	2,144.2 a,b	370.2	1,742.8	2,730.4	1,935.3 b	203.8	1,685.6	2,254.2
Implant–implant (III)	2,689.3 a	484.2	1,752.4	3,000.8	2,483.5 a	149.8	2,297.2	2,724.2

Values in one column denoted by the same letter do not differ with statistical significance (post-hoc Scheffé)

MV mean values, *SD* standard deviations, *Min* minima, *Max* maxima

total fracture of the restorations, Hertzian cone cracks were visible at the spherical loading site within the veneer layer. It could be hypothesised that failure of the specimens might be initiated due to propagation of these localised contact damage cracks. However, Kelly et al. showed that failure of all-ceramic FDPs occurred in the connector area, originating from the interface between the core and veneer ceramics and not from the contact damage [20]. These findings are supported by our results: SEM analysis revealed that with all tested FDPs the fracture origin was located in the zirconia framework close to the core/veneer interface at the gingival embrasure (Fig. 6).

If a dental restoration is to remain in service in the long-term, its load-bearing capacity should exceed maximal natural bite forces. Maximum chewing forces somewhere between 600 and 800 N have been recorded in the molar region [30–32]. The forces recorded in our experiment enormously exceed these values. At the same time, the tested samples were four-unit restorations, i.e., long-spanned. As the length of the prosthesis increases, stress intensity increases as well, which may be destructive for all-ceramics [33]. Thus, long-spanned restorations are more susceptible to failure. Nevertheless, the results of our study showed that the choice of complex all-ceramic restorations with all different support scenarios can be considered safe for posterior areas as well. Finally, it should be mentioned that the fracture strength demonstrated by our samples lies higher than previously recorded values for three-unit [23, 24] or even for four-unit restorations [11, 12].

Statistical analysis revealed a significant impact of artificial ageing on the fracture strength of the all-ceramic FDPs (p=0.032). A decrease in strength—about 200 N—was demonstrated by all groups after ageing. Therefore, the study hypothesis - that artificial ageing significantly influences the load-bearing capacity of the bridgeworks - has been confirmed. Heterogeneous results were reported by other studies also investigating the effect of thermomechanical preloading on the load-bearing capacity of zirconia FDPs. Some surveys did not find a statistically significant effect of artificial ageing protocols [8–10]. In contrast, in other investigations ageing was proven to have a detrimental influence on the long-term strength of four-unit FDPs [11, 12]. Recently, Rosentritt et al. determined various ageing protocols on three-unit restorations and reported a significant effect on fracture strength due to thermomechanical cycling [13]. An increase in load-bearing capacity has only been reported in a single study [24]. However, in the latter study, model teeth were made of alloys while a recorded decrease in force of 30 N was taken as indicating failure, without there being bulk fracture of the framework in all samples. These limitations in the study design may have caused the misleading increase in fracture strength. Further investigations on the impact of ageing on standardised zirconia specimens revealed an increase in the tetragonal-to-monoclinic transformation [5]. Borchers et al. also reported an increase in superficial monoclinic content from 2% to 4–10% after thermomechanical stressing [3]. Nonetheless, this phenomenon did not extend deep enough into the material mass to significantly reduce the mean fracture strength of the specimens. Therefore, the authors attributed the decrease in the load-bearing capacity observed in dental prostheses after preloading not to LTD, but to other factors—such as degradation of the veneering layer, fatigue of the veneer-framework interface or stresses provoked by the t→m transformation of the crystals.

In the present study, the type of abutment support appears to have a significant influence on the load-bearing capacity of the zirconia restorations. The difference was significant both for the aged and the non-aged groups and hence the second study hypothesis was also confirmed. Rigid support provided by implants was favourable when compared to that provided by the simulated periodontal ligament in all groups. The latter has also been confirmed by Vult von Steyern et al. [34]. Zirconia is prone to tensile stresses while tensile stresses increase through resilient support. This susceptibility may have been responsible for the strength degradation shown for the resiliently retained samples. Dittmer et al. [14] also came to the conclusion that resilient support may be unfavourable for all-ceramics. Finally, implant-to-tooth interconnected prostheses exhibited a medium load-bearing capacity, i.e., the values recorded for these groups lay between rigidly assisted and resiliently retained restorations. The rigid abutment (implant) of the mixed FDPs may have contributed to a better fracture strength while the other (resiliently supported tooth analogue) acted unfavourably. According to the results of this study, splinted prostheses may be a viable treatment option, as these restorations exhibit favourable mechanical characteristics. Other factors should be investigated before their clinical application, including the unequal distribution of stresses due to the mobility mismatch of the retainers.

Conclusions

The application of thermomechanical cycling causes a decrease in the load-bearing capacity of zirconia FDPs. Despite the influence being statistically significant, the recorded values still lie within acceptable limits. Whether LTD is responsible for this decrease or not remains to be clarified. The fracture strength of the all-ceramic FDPs greatly exceeded natural maximal bite forces, despite their being long-spanned (four-unit). Resilient support was demonstrated to be unfavourable for such prostheses. Finally, implant-to-tooth-interconnected restorations demonstrated sufficient load-bearing capacity even after ageing.

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Conflict of interest The authors declare that they have no conflict of interest.

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